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This Final Report covers a three-year research program in basic laser physics and laser device technology. Research covered four main projects: synch-pumped OPO mode locking techniques; definitive measurements of a fundamental excess quantum noise mechanism; development of improved methods for defining and measuring transverse beam quality; and work on new unstable resonator and etched-mirror concepts. We believe this program has been particularly productive.

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RESEARCH IN LASER OSCILLATOR PHYSICS

AND LASER DEVICE PERFORMANCE

Final Technical Report to

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

under Contract No. F49620-92-J-0229

for the period

1 April 1992—31 March 1995

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June 1995

FINAL REPORT ON AFOSR GRANT F49620-92-J-0229

Professor A. E. Siegman
Edward L. Ginzton Laboratory
Stanford University, Stanford CA 94305
1 April 1992–31 March 1995

I. Introduction

This is the final report on what we believe has been a very productive AFOSR-sponsored university research program in basic laser physics and laser device technology under the direction of Professor A. E. Siegman at Stanford University for the period April 1, 1992, through March 31, 1995.

The proposal for this program called for research to be carried out in four areas:

- "Work on synch-pumped OPO mode locking techniques in order to obtain ultrashort pulses in the near and middle infrared...";
- "Definitive measurements of a fundamental excess quantum noise mechanism in order to determine the quantum limit on the future performance of ultrastable laser oscillators...";
- "The development of improved methods for defining and measuring the transverse beam quality of real laser devices..."; and
- "Work on new unstable resonator and etched-mirror concepts for semiconductor diode lasers".

An overall summary of the success of the current program in achieving each of these objectives is given in the following sections.

II. Generation of Ultrashort Infrared Optical Pulses

All objectives in this portion of our research program were fully met during the contract period. In particular we built and operated the first singly-resonant continuous-wave mode-locked OPO to be successfully synch-pumped by a conventional cw lamp-pumped Nd:YAG laser, thereby making possible the generation of tunable IR pulses from a standard and widely available laser system which can be found in many laser laboratories. The results concerning this oscillator were published in the journal article:

J. Chung and A. E. Siegman, "Singly resonant continuous-wave mode-locked KTiOPO4 optical parametric oscillator pumped by Nd:YAG laser", *J. Opt. Soc. Am. B* **11**, 2201–2210 (November 1993).

These results and related research also led to the completion of Dr. Joon Chung's PhD dissertation, and to an invited paper given by Dr. Chung at an international symposium on ultrafast optical technology:

J. Chung, *Ultrashort Pulses in the Infrared from Synchronously Pumped Optical Parametric Oscillators*, PhD dissertation, Department of Electrical Engineering, Stanford University (March 1993).

J. Chung and A. E. Siegman, "Continuous wave synchronously pumped optical parametric oscillator for picosecond infrared pulse generation" (invited paper), presented at VIIIth International Symposium on Ultrafast Processes in Spectroscopy (UPS '93), Vilnius, Lithuania (26-30 September 1993).

Related work on a simple method to achieve substantially shorter mode-locked pulses from the widely available lamp-pumped Nd:YAG laser has also now been published:

J. Chung and A. E. Siegman, "Optical-Kerr-enhanced mode locking of a lamp-pumped Nd:YAG laser", *IEEE J. Quantum Electron.* **QE–31**, 582–590 (March 1995).

These results complete the work of Professor Siegman's group in ultrashort pulse technology generally.

III. Measurement of Excess Quantum Noise Effects

Another primary goal of our group for the past several years has been to obtain a clearcut experimental confirmation of the large excess spontaneous emission or excess quantum noise effect first proposed by Petermann for gain-guided semiconductor diode lasers. An essentially identical excess noise emission was later shown theoretically by our group to be expected in a much broader class of nonorthogonal or "biorthogonal" laser resonators, including particularly the widely used class of unstable optical resonators. Clear experimental confirmation of this interesting quantum noise effect was, however, still neeeded.

A major contribution to this experimental confirmation has now been achieved under this contract through direct measurements of greatly enhanced Schawlow-Townes phase fluctuations in the oscillation sidebands of a miniature monolithic diode-pumped Nd:YAG laser having a gain-guided unstable resonator cavity. Two nearly identical stable and unstable cavity Nd:YAG lasers were developed for this research, and dramatically different Schawlow-Townes fluctuations were then measured for these two lasers under essentially identical operating conditions. These excess quantum noise results have now been published in a journal article and also reported in a talk at the 1993 QELS meeting:

Y.-J. Cheng, P. L. Mussche and A. E. Siegman, "Measurement of laser quantum frequency fluctuations using a Pound-Drever stabilization system", *IEEE J. Quantum Electron.* **QE–30**, 1498–1504 (June 1994).

P. L. Mussche, Y.-J. Cheng and A. E. Siegman, "Experimental confirmation of excess spontaneous emission in a laser oscillator with nonorthogonal transverse eigenmodes", presented at QELS '93, Baltimore, Maryland (May 1993).

This and related work led to the completion of Dr. Paul Mussche's PhD dissertation:

P. Mussche, *Excess Quantum Linewidth in Lasers with Nonorthogonal Eigenmodes*, PhD dissertation, Department of Electrical Engineering, Stanford University (December 1994).

In the course of this work we also discovered an unanticipated phenomenon in which the unusual mode properties of the gain-guided unstable-resonator cavity led to a significant modification of its relaxation oscillation behavior, as reported in the publication:

Y.-J. Cheng, P. L. Mussche and A. E. Siegman, "Cavity decay rate and relaxation oscillation frequency in unconventional laser cavities", *IEEE J. Quantum Electron.* **QE–31**, 391–398 (February 1995).

Since the measurement of relaxation oscillation frequencies is widely regarded as a convenient and useful way of determining the cavity losses in an oscillating laser, the identification of this anomalous behavior in certain kinds of laser resonators was of some practical importance.

Our work on this fundamental quantum noise effect has also met with external recognition. A lengthy report covering earlier theory and recent experimental results will appear in a Special Issue of Applied Physics B published as a Festschrift for Herbert Walther, Director of the Max-Planck-Institute for Quantum Optics in Garching, Germany, and a report on this work was also presented as a plenary talk at a symposium in Japan:

A. E. Siegman, "Lasers without photons—or should it be lasers with too many photons", *Appl. Phys. B* **60**, 247–257 (February/March 1995).

A. E. Siegman, "Laser beams and resonators: Normal modes and not so normal modes" (Plenary Talk), in *Laser and Superconductivity: Sixth Interntional Form on the Frontier of Telecommunications Technology*, Kobe, Japan (December 1994).

In addition we will present an invited talk on this and more recent work at the June 1965 Rochester Conference on Coherence and Quantum Optics:

A. E. Siegman, "Lasers Without Photons" (invited paper), to be published in *Coherence and Quantum Optics VII*, ed. by J. Eberly, L. Mandel and E. Wolf, Plenum Press, New York (1995).

For various practical reasons all our experimental results to date were obtained using a gain-guided or "gain-confined" unstable resonator design rather than a true hard-edged unstable resonator design. To confirm beyond question that these excess noise fluctuations arise from transverse mode properties and not gain-guiding effects we have recently developed a miniature diode-pumped Nd:YVO4 laser having a conventional hard-edged unstable cavity and we are now proposing to do one brief additional set of quantum noise measurements with this design. Our quantum noise measurements should then be finished with completion of an additional PhD dissertation by Yuh-Jen Cheng during the summer of 1995, shortly after the end of the contract period.

IV. Definition and Measurement of Laser Beam Quality

Work carried out during the current contract period by our group in collaboration with industrial developments by M. Sasnett and T. Johnston, Jr., of Coherent Optics and several other commercial firms has now brought into general use much improved methods for characterizing "laser beam quality"—that is, the transverse mode properties and the propagation properties of real laser beams—for workers in the laser field and users of practical laser devices.

This work began with Coherent's development of the first commercially available real-time beam propagation measuring instrument, combined with our work under this contract in the general area of the definition and understanding of laser beam quality and the application of beam quality measurements to the study of laser device physics. This work has now won wide acceptance as evidenced by the increasing number of journal publications and specification sheets for all types of lasers which now include numerical values of the beam propagation factor M^2 among the data which is reported. A number of invited talks and review publications from our group helped to spread the beam-quality gospel during the current period, including:

A. E. Siegman, "High power laser beams: defining, measuring and optimizing transverse beam quality" (invited paper), in *Gas Flow and Chemical Lasers (GCL '92): Proc. SPIE* **1810**, Heraklion, Crete (September 1992).

A. E. Siegman, "Defining, measuring, and optimizing laser beam quality" (invited paper), in *Laser Resonators and Coherent Optics: Modeling, Technology, and Applications; Proc. SPIE 1868*, Los Angeles, California (January 1993).

A. E. Siegman, "Defining and measuring laser beam parameters" (invited paper), in *Laser Beam Characterization*, ed. by P. M. Mejias, H. Weber, R. Martinez-Herrero and A. Gonzalez-Urena, (SEDO (Optical Society of Spain), Madrid, Spain, June 1993); pp. 1–22..

G. Nemes, J. A. Ruff and A. E. Siegman, "The beam quality concept applied to high power lasers", in *Laser Interaction and Related Plasma Phenomena: 11th International Workshop (AIR Conference Proceedings, Vol. 318)*, Monterey, California (October 1993).

A. E. Siegman, "Defining and Measuring Laser Beam Quality", in *Solid State Lasers: New Developments and Applications*, ed. by M. Inguscio and R. Wallenstein, (Plenum Press, New York, 1994); pp. 13–28.

Experimental results from our group on practical aspects of laser beam quality measurement and on the use of beam quality measurements to study basic laser physics were also reported during the contract period in various papers and talks, including:

A. E. Siegman, "Beam quality measurements on diode lasers", presented at Diode Laser Technology Program (DLTP) Meeting, Fort Walton, Florida (21–23 April 1992).

J. A. Ruff and A. E. Siegman, "Single pulse laser beam quality measurements using a CCD camera system", *Appl. Opt.* **31**, 4907–4909 (20 August 1992).

M. D. Duncan and J. A. Ruff, "An M^2 beam quality meter for pulsed lasers", presented at Optical Society of America Annual Meeting, Albuquerque, New Mexico (September 1992).

A. E. Siegman and S. W. Townsend, "Output beam propagation and beam quality from a multimode stable-cavity laser", *IEEE J. Quantum Electron.* **QE–29**, 1212–1217 (April 1993).

Particular attention was given to the effect of spherical aberration on laser beam quality, as reported in:

A. E. Siegman and J. Ruff, "Effects of spherical aberration on laser beam quality", in *Laser Energy Distribution Profiles: Measurement and Applications: Proc. SPIE* **1834**, (November 1992).

A. E. Siegman, "Analysis of laser beam quality degradation caused by spherical aberration", *Appl. Opt.* **32**, 5893–5901 (20 October 1993).

J. A. Ruff and A. E. Siegman, "Measurement of beam quality degradation due to spherical aberration in a simple lens", *Opt. Quantum Electron.* **26**, (1994).

We also developed some unexpected (and somewhat controversial) results showing that in a very real sense the beam quality of antiphased laser arrays is actually not improved when these beams are corrected and brought into phase by binary phase plates. These results were reported in a journal article and conference talk:

A. E. Siegman, "Binary phase plates cannot improve laser beam quality", *Opt. Lett.* **18**, 675–677 (1 May 1993); also presented at LEOS '93 (1993 LEOS Annual Meeting), San Jose, California (17 November 1993).

With the collaboration of a visiting scientist from Romania, Professor George Nemes, we also developed a general theory and proposed a powerful but simple method for measuring all the basic parameters of more general laser beams, including arbitrary nonorthogonal or "twisted" laser beams, as reported in the journal article:

G. Nemes and A. E. Siegman, "Measurement of all ten second moments of an astigmatic beam by the use of rotating simple astigmatic (anamorphic) optics", *J. Opt. Soc. Am. A* **11**, 2257–2264 (August 1994); also presented at Optical Society of America Annual Meeting, Toronto, Canada (October 1993).

Dr. Nemes, who has contributed greatly to work in our group at no direct charge to the contract, has also presented an extensive list of other publications and talks on various generalized laser beam properties during the contract period, including:

G. Nemes, V. M. Feru and G. P. Ispasoiu, "Toward a generalized optical radiometry: a phase-space approach", presented at Optical Society of America Annual Meeting, Albuquerque, New Mexico (September 1992).

G. Nemes, V. M. Feru and G. P. Ispasoiu, "A phase-space point of view on optical detection", presented at Optical Society of America Annual Meeting, Albuquerque, New Mexico (September 1992).

G. Nemes and A. G. Kostenbauder, "Optical systems for rotating a beam", in *Laser Beam Characterization*, ed. by P. M. Mejias, H. Weber, R. Martinez-Herrero and A. Gonzalez-Urena, (SEDO (Optical Society of Spain), Madrid, Spain, June 1993); pp. 99–109..

G. Nemes, "Measuring and handling general astigmatic beams" (invited paper), in *Laser Beam Characterization*, ed. by P. M. Mejias, H. Weber, R. Martinez-Herrero and A. Gonzalez-Urena, (SEDO (Optical Society of Spain), Madrid, Spain, June 1993); pp. 325–358..

J. Serna and G. Nemes, "Decoupling of coherent gaussian beams with general astigmatism", *Opt. Lett.* **18**, 1774–1776 (1 November 1993).

G. Nemes, "Synthesis of general astigmatic optical systems, the detwisting procedure, and the beam quality factors of general astigmatic beams" (invited lecture), presented at Laser Beam Characterization Meeting, Berlin, Germany (May-June 1994).

The wide interest in properly characterizing laser beam quality was also evidenced by two international meetings on this topic (Madrid 1992 and Berlin 1994) at both of which members of our group were plenary or invited speakers; by an international standards effort in this area undertaken by the ISO, in which we have also participated; by the emergence of at least half a dozen commercial instruments for making beam propagation and M^2 measurements; and finally by the increasing use of these concept by laser workers and laser authors, as mentioned above. While the basic concepts of laser beam propagation and its measurement are thus now well established both theoretically and experimentally, there are still a few areas of difficulty, for example in interpreting the second-moment theory for certain limiting beam profiles, and in practical methods for evaluating second moments of real measured beam profiles so as to correct for baseline offset and noise. We therefore hope to continue a small amount of limited future work to address these and other unresolved issues in the beam propagation theory.

V. Optical Resonators and Semiconductor Diode Lasers

The research topics of unstable optical resonators, semiconductor diode lasers using unstable resonators, and etched-mirror diode lasers in general, have been the areas of work under this contract in which the newest and most recent developments have recently been emerging, and in which the most future work is planned. Recent results under the present contract include the following.

a) Unstable resonator theory and applications:

The unstable optical resonator was of course invented in this group under AFOSR support some time ago. A few straightforward extensions and potential applications of the unstable-resonator concept were published early in the current contract period, as follows:

A. E. Siegman, "Performance limitations of the self-filtering unstable resonator", *Opt. Commun.* **88**, 295–297 (1 April 1992).

A. E. Siegman, "Stable-unstable resonator design for a wide-tuning-range free electron laser", *IEEE J. Quantum Electron.* **QE–28**, 1243–1247 (May 1992).

A. E. Siegman, "Advances in Laser Resonator Design Using Variable Reflectivity Mirrors", in *Tutorials in Optics*, ed. by D. T. Moore, (Optical Society of America, Washington, DC, 1992); pp. 65–84..

We also noted above that as part of the quantum noise experiments discussed in Section III of the report we developed a small diode-pumped solid-state laser employing a conventional hard-edged unstable resonator. In this laser a 3%-doped Nd:YVO4 slab 3 mm square and 1 mm thick was pumped with a several-watt diode laser in a 300 μm diameter spot. An unstable-resonator mirror fabricated using photolithographic techniques to produce a 300 μm diameter gold spot on an antireflection-coated lens surface with a radius of curvature chosen to produce a geometric magnification $M \approx 1.2$ was placed approximately 1 mm in front of the vanadate slab. A preliminary report on this device has been accepted for presentation in:

> G. Fanning, Y.-J. Cheng and A. E. Siegman, "Axially diode pumped unstable resonator Nd:YVO4 laser", to be presented at LEOS '95, San Francisco (November 1995)

and a journal article will be prepared in the near future.

We developed this laser initially to in the final set of excess quantum noise experiments mentioned in Section III. The successful operation of the initial device led us, however, to look more seriously at this general approach for obtaining improved performance in medium to high-power axially pumped solid-state lasers, and we now believe this unstable-resonator design may be of considerable practical interest for making simple axially pumped solid-state lasers having substantially increased mode volume and hence power output, while retaining single-transverse-mode beam quality.

Axial diode pumping of solid-state lasers is attractive because it concentrates the pump light within the laser volume while permitting small, simple, quasi monolithic laser designs. The mode diameter and mode volume for a typical stable-cavity laser resonator of this type is, however, necessarily very small, e.g., a mode diameter on the order of 50 μm for a cavity a few mm long. This small diameter severely limits the power available from the device if it is to operate in a single TEM_{00} transverse mode, and also imposes difficult requirements on how the diode pumping power must be focused into this small mode volume. Workers attempting to obtain higher output powers, using for example diode laser arrays rather than single-mode pump diodes, have thus been forced to consider more complex structures such as side-pumped or slab laser designs. Our unstable-resonator design, however, inherently permits much larger transverse mode diameters for the same cavity length, e.g., several hundred μm diameter for a cavity only 1 or 2 mm in length. This ten-fold increase in mode diameter means a potential increase in mode volume and hence power output capability of up to 100 times, while at the same time taking advantage of the high transverse mode discrimination and single transverse mode oscillation properties that are a distinguishing characteristic of the unstable resonator. In addition spectral observations show that our laser, because of its short length, oscillates under most conditions in a single axial mode. Another advantage is that this greatly eases the optical focusing requirements for the diode pump beam or beams into the mode spot. With the larger diameter for the pumped region it may be possible to use nonimaging light concentrators, eliminating the circularizing optics and greatly simplifying the complexity of pump beam collimation and focusing. Our intention is thus to explore in future work the potential advantages of this design approach to higher-power axially pumped solid-state lasers.

b) Unstable-resonator semiconductor diode lasers:

We have for a long time been interested in finding a way to apply the general concept of the unstable optical resonator to wide-stripe semiconductor diode lasers in order to obtain greatly increased output power from the wider stripe while at the same time avoiding the filamentation and multiple transverse mode problems that ruin the beam quality of usual wide-stripe diodes. We believe that some form of unstable-resonator wide-stripe diode laser could be superior to the multiple-stripe phased-array high-power diode structures that have been the subject of a large amount of development effort to date—especially since the desired phased-array operation of these structures has proven to be elusive.

As one step toward this objective, during the current program we experimented with a thermally induced divergent-stripe unstable laser concept. In this approach resistive heater stripes on both sides of a wide laser stripe produce temperature and index gradients across the stripe which lead to divergent focusing and unstable-resonator thermal mode control, while still allowing for cleaved planar facet mirrors at both ends of the diode. Tests on initial devices of this type indeed showed clear evidence of thermally induced unstable-resonator behavior and significantly improved beam quality with increased heating, as described in a LEOS conference presentation:

Y. Sun, S. A. Biellak, G. Fanning and A. E. Siegman, "Temperature induced unstable-resonator semiconductor lasers", presented at LEOS '93: 1993 LEOS Annual Meeting, San Jose, California (November 1993).

However we also encountered practical difficulties in making current contacts to these structures and in obtaining adequate thermally induced magnification in the stripe itself.

In a more direct and promising attack on the problem, in collaboration with Professor Simon Wong at the Stanford Center for Integrated Systems (CIS) we have recently been able to employ reactive ion etching (RIE) to fabricate unstable-resonator mirrors directly onto diode laser wafers, with test versions of these devices yielding good experimental results. The etched mirror surfaces appear to be of good quality, and we find that the largest-magnification diode laser has an M^2 value that approaches $M_x^2 \approx 1.25$, or nearly diffraction limited, at the largest output powers. In these structures the M^2 value actually improves at high output levels, in contrast to conventional wide-stripe diodes. Our initial results with etched-mirror unstable-resonator diodes were reported at the 1994 CLEO meeting:

> S. A. Biellak, G. Fanning, Y. Sun, S. S. Wong and A. E. Siegman, "High power diffraction-limited reactive-ion-etched unstable-resonator diode lasers", presented at CLEO '94, Anaheim, Calif. (May 1994)

and a journal manuscript is now in preparation. We believe these are the first experiments demonstrating unstable resonators directly etched onto a diode laser, so as to permit lithographic fabrication of large numbers of lasers directly on a single wafer.

c) Diode laser beam steering methods:

During the thermally controlled divergent-stripe experiments mentioned above we also observed experimentally that by heating only one side of the stripe at a time we could obtain a thermally controlled linear index gradient across the stripe, which in turn produced precise and continuous thermally controlled lateral displacement and far-field beam steering of a near-gaussian output beam from these lasers, as reported in:

> Y. Sun, C. G. Fanning, S. A. Biellak and A. E. Siegman, "Thermally controlled lateral beam shift and beam steering in semiconductor lasers", *IEEE Photonics Technol. Lett.* **7**, 26–28 (January 1995).

We have since been able to interpret these results in terms of complex Hermite gaussian beam propagation in offset gain-guided plus index-guided waveguide structures, and a journal publication on this analysis is currently in preparation:

> Y. Sun and A. E. Siegman, "Optical mode properties of parabolic offset gain and index guiding structures", *IEEE J. Quantum Electron.* to be submitted (1995).

This work also led to a new analytic solution for spatial solitons in wide-stripe semiconductor laser structures which has been accepted for publication in:

> Y. Sun, "Analytic spatial solitary wave modes of the coupled wave-carrier equations in a semiconductor waveguide", *Opt. Lett.* **20**, accepted for publication (1995).

The etched mirror technology mentioned above has also led us to other interesting diode-laser beam steering developments. In a project carried out in collaboration with Professor Connie Chang-Hasnain's group in the Ginzton Laboratory we fabricated a number of novel "fan" lasers having multiple laser stripes with independently etched mirrors oriented in a fan array. Each individual gain stripe can then be turned on independently with the beams all passing through a common focal point but traveling in different directions. One thus has a simple structure whose output beam can be digitally scanned in purely electronic fashion, or used to produce a dozen or more independently modulatable output beams. Combined with simple optics this can be used to drive multiple channels in a multiplexed fiber-optic communications scheme, or to write or read multiple pixels in an electronically scanned printer or image scanning application. This work was first presented as a post-deadline paper in a major meeting on semiconductor lasers, followed by a short journal article and a more detailed conference presentation:

Y. Sun, D. Francis, S. Biellak, A. E. Siegman and C. J. Chang-Hasnain, "Beam steerable diode laser with a large steering range and resolvable spots", presented at 14th IEEE International Semiconductor Laser Conference, Hawaii (21 September 1994)

Y. Sun, D. Francis, S. Biellak, A. E. Siegman and C. J. Chang-Hasnain, "Beam steerable semiconductor lasers with a large steering range and resolvable spots", *Electron. Lett.* **30**, 2034–2035 (24 November 1994).

D. Francis, Y. Sun, S. Biellak, A. E. Siegman and C. J. Chang-Hasnain, "Optical characteristics of a beam-steerable semiconductor fan laser array", to be presented at *Conference on Lasers and Electro-Optics (CLEO '95)*, Baltimore, MD (May 1995).

Appropriate patent disclosures under this contract are also currently being processed.

q) Other etched-mirror resonator topics

The etched-mirror technology described above also permits us to experiment with other interesting resonator designs for diode lasers. In particular we have recently fabricated a number of diode lasers having conventional gaussian stable resonators, with results to be reported in:

S. A. Biellak, Y. Sun, S. S. Wong and A. E. Siegman, "Lateral mode behavior of reactive-ion-etched stable-resonator semiconductor lasers", *J. Appl. Phys.*, accepted for publication (1995).

S. A. Biellak, Y. Sun, S. Wong and A. E. Siegman, "A Monolithic Stable-Resonator Semiconductor Laser", to be presented at 1995 Semiconductor Lasers: Advanced Devices and Applications, Keystone, Colorado (21–23 August 1995).

The general conclusion of these studies is that, for various reasons, conventional stable resonators are not likely to be useful for practical diode lasers, but since the theory of conventional stable resonators is very well understood, comparisons between theory and experiment on stable-resonator diodes can be a good way to obtain detailed information about the focusing and mode guiding properties of gain stripes in diode lasers.

We have also recently made a few measurements of the amplified spontaneous emission and oscillation properties of closed "stadium" structures fabricated by etching techniques on diode laser wafers. The properties of such stadium structures are of interest because of the great current interest among nonlinear dynamicists in the periodic orbits, "scars', and other chaotic and eigenmode properties of such structures [see for example the review article "Postmodern Quantum Mechanics" by E. J. Heller and S. Tomsovic in *Physics Today* (July 1993)]. The devices we can fabricate are essentially "leaky" analogs of such structures containing controllable internal gain, so that we can hope to observe directly the eigenmode patterns in which these structures oscillate, and see how (or whether) these laser modes will relate to the ray or eigenmode properties predicted by theoreticians. We plan to carry out some further work on this topic including interpreting the results we have already seen from these structures.

VI. Conclusions

We believe this has been a very productive program as documented by approximately 25 journal publications and refereed book sections and conference proceedings, 2 PhD dissertations, and some 15 other lectures and talks, many of them invited. More important, the program has incorporated a productive mixture of basic science and theory (e.g., the quantum noise and theoretical beam propagation studies) together with applied results directly connected to practical laser applications and useful laser devices (e.g., the beam quality and beam propagation measurement technology, ultrashort pulse generation, unstable diode lasers with improved beam quality and power output, unstable solid-state lasers, and steerable laser developments). Several of the topics studied in this program can now be regarded as completed, while others point to promising advances for further development in the practical applications of lasers and laser technology.